

Circumstellar Habitable Zones of Binary Star Systems in the Solar Neighborhood

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ABSTRACT

Binary and multiple systems constitute more than half of the total stellar population in the Solar neighborhood (Kiseleva-Eggleton & Eggleton 2001). Their frequent occurrence as well as the fact that more than 70 (Schneider et al. 2011) planets have already been discovered in such configurations - most notably the telluric companion of α Cen B (Dumusque et al. 2012) - make them interesting targets in the search for habitable worlds. Recent studies (Eggl et al. 2012b; Forgan 2012) have shown, that despite the variations in gravitational and radiative environment, there are indeed circumstellar regions where planets can stay within habitable insolation limits on secular dynamical timescales. In this article we provide habitable zones for 19 near S-Type binary systems from the Hipparchos and WDS catalogues with semimajor axes between 1 and 100 AU. Hereby, we accounted for the combined dynamical and radiative influence of the second star on the Earth-like planet. Out of the 19 systems presented, 17 offer dynamically stable habitable zones around at least one component. The 17 potentially habitable systems contain 5 F, 3 G, 7 K and 16 M class stars. As their proximity to the Solar System ($d < 31$ pc) makes the selected binary stars exquisite targets for observational campaigns, we offer estimates on radial velocity, astrometric and transit signatures produced by habitable Earth-like planets in eccentric circumstellar orbits.

Key words: astrobiology — habitable zones — binaries

1 INTRODUCTION

The discovery and confirmation of terrestrial bodies orbiting other stars (e.g. Dumusque et al. (2012); Borucki et al. (2012); Borucki (2011); Léger et al. (2009)) has generated enormous public as well as scientific interest. It has shown that after a mere two decades of exoplanetary research finding potentially habitable worlds around other stars seems to be almost within our grasp. Close-by stars and stellar systems are thereby premium targets, as they tend to offer reasonable signal to noise ratios (SNRs) for photometry and radial velocity as well as comparatively large astrometric amplitudes (Beaugé et al. 2007; Malbet et al. 2011; Guedes et al. 2008; Eggl et al. 2012a). As more than half of the stars in the Solar neighborhood are members of binary or multiple systems (Kiseleva-Eggleton & Eggleton 2001),

it is not surprising that more than 70 planets in or around binary-stars have been discovered (Schneider et al. 2011) despite the current observational focus on single star systems. Even-though NASA's *Kepler* mission has been quite successful in finding circumbinary planets (e.g. Welsh et al. (2012); Orosz et al. (2012); Doyle et al. (2011)) we will focus on binary-star systems with potential *circumstellar* habitable zones (HZs) in this study. In fact, most of the planets discovered in double stars are in these so-called S-Type configurations (Rabl & Dvorak 1988; Roell et al. 2012), where the planet orbits one star only. The telluric companion of α Cen B is such an example (Dumusque et al. 2012).

An interesting question in this regard is doubtlessly: Can S-Type binary stars harbor habitable worlds? Already Huang (1960) and Harrington (1977) and more recently Forgan (2012) investigated the effects such configurations have on the insolation hypothetical planets would receive. Eggl et al. (2012b) (in the following referred to as EG12) were able to derive analytic expressions to find HZs in binary star systems unifying dynamical and radiative balance models for S-Type binary star - planet systems. While

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the exact manner in which planets form in tight binary star systems is still hotly debated in astrophysical literature - see for instance Müller & Kley (2012); Batygin et al. (2011); Paardekooper & Leinhardt (2010); Thebault (2011) and references therein, the discovery of α Cen B b has made the existence of terrestrial planets in S-Type binary star systems an observational fact. Opinions still differ on whether it is theoretically possible that planets in α Centauri's HZs can form on stable orbits. Even though classical N-body simulations with best case accretion scenarios seem to be able to produce terrestrial planets near the HZs of the α Centauri system (Quintana & Lissauer 2010; Guedes et al. 2008), Thébault et al. (2009, 2008) concluded that even when gas drag is included the encounter velocities between kilometer sized planetesimals would lead to erosive collisions, thus making constant accretion unlikely. However, in their model they did not include a self-consistent evolution of the gas disc, nor did they consider planetesimal self gravitation or re-accretion of collisional debris. Paardekooper & Leinhardt (2010) used a self consistent disc model with planetesimals. They were able produced accretion friendly scenarios when the collision frequency was sufficiently high to prevent orbital dephasing. Other possible solutions to the problem of high encounter velocities range from including planetesimal and embryo migration Payne et al. (2009) over mild inclination of planetesimal discs with respect to the binary's orbit (Xie et al. 2010) to more realistic radiative modeling of the system's gaseous disc (Müller & Kley 2012).

Eggl et al. (2012a) show that even if additional Earth-like planets in α Centauri do exist, it is not an easy task to find them given current observational limitations in radial velocity resolution. The RV signal semi amplitude of α Cen B b was near the current edge of feasibility with δ RV $\simeq 50$ cm/s, whereas accuracies lower than 10 cm/s would be necessary to discover telluric planets in α Cen B's HZs. Astrometry is not much more helpful in this case, as the necessary astrometric amplitudes to detect habitable worlds in α Centauri will only be available near the end of the GAIA mission's lifetime (Hestroffer et al. 2010).

In this study we tackle the question whether there are S-Type systems in the Solar neighborhood that might make for easier targets. For this purpose we select 19 S-Type binary systems from "The Washington Visual Double Star Catalog" (WDC) (Mason et al. 2012) with well determined stellar parameters that lie within a distance of 31 pc from the Solar System, and calculate HZs for each stellar component using the analytic method presented in Eggl et al. (2012b). We provide estimates on the RV and astrometric (AM) root mean square (rms) signal strengths expected for an Earth-like planet orbiting at the borders of a system's HZs. Furthermore, we present likely transit depths for potentially transiting habitable planets in co-planar S-Type double star systems.

This article is structured as follows: First, we will discuss the selection criteria for the 19 systems investigated (section 2). After a brief summary of the main factors that determine habitability for terrestrial planets in binary star systems (section 3), the issue of dynamical stability of planets in such configurations is addressed in section 4. Our results - tables with HZ borders and signal strength estimates - are presented and discussed in sections 5 and 6. Current

problems in modeling tidal locking of planets in binary systems are mentioned in section 7. A summary (section 8) concludes this study.

2 SELECTION OF BINARY STAR SYSTEMS

We preselected all detached binaries with semimajor axes $1 < a_b < 100$ AU using the stellar orbital parameters provided in the WDC, in order to find suitable S-Type systems in the Solar neighborhood where Earth-like planets in HZs could be detectable. Hereby, we only considered systems within a distance of $d < 31$ pc from our Solar System as determined by the Hipparchos mission (van Leeuwen 2007). Together with the prerequisite that the binaries' orbital elements had to be available, the afore mentioned restrictions reduced the number of admissible double star systems to 313. Furthermore, only double star configurations with known spectral types of both components were used. Peculiar spectra that might have been classified incorrectly by Hipparchos like HIP 17544 & 73695 were also excluded, narrowing the set of candidate systems from 313 to 35. The ultimate selection criterion consisted of calculating the binaries' periods using bolometric luminosity derived masses together with the semimajor axes given in WDS and comparing them to the observed binary periods. The stellar bolometric luminosities and masses required for this purpose were derived as follows: With the distances available through Hipparchos data the systems' absolute visual magnitudes could be calculated. In order to assess the bolometric luminosities of the binary sample, we performed bolometric corrections (BC) of the absolute visual magnitudes using the polynomial fits by Flower (1996). The required effective temperatures were estimated via spectral type and luminosity using the ATLAS9 catalog of stellar model atmospheres (Castelli & Kurucz 2004). We then calculated the binaries' periods using the masses derived via the mass-luminosity relations given in Salaris & Cassisi (2005). Only those systems who's derived periods did not deviate more than 11% from the observed periods were selected for the final sample. Stellar and orbital parameters for the final set of 19 S-Type binary systems are presented in Table 1.

In the next section we will briefly discuss the main points on how to determine HZs for these S-Type binary systems.

3 HABITABILITY OF EARTH-LIKE PLANETS IN S-TYPE BINARY STAR SYSTEMS

The most pronounced difference between determining classical HZs and HZs for Earth-like planets in binary star systems lies in the assumption that planetary orbits are basically circular. In fact, the well known borders defined by Kasting et al. (1993) are built on the premises that planetary insolation will change only on stellar evolutionary timescales. Thus, the planet is thought to remain more or less at the same distance from its host star on a circular orbit. This assumption is implicitly made in almost all recent works, e.g. Kane & Gelino (2012); Pierrehumbert & Gaidos (2011); Kaltenegger & Sasselov (2011). However, in three body systems, such as the planet - binary star configurations

Table 1. Orbital and stellar parameters of the 19 investigated binary star systems. The values of parameters printed in bold letters are taken from (Mason et al. 2012; van Leeuwen 2007), the others were derived as described in section 2. The binary’s eccentricity and semimajor axis are denoted by a_b and e_b ; I is the system’s inclination to the plane of the sky. A binary components’ masses are symbolized by M_A and M_B , their respective luminosities by L_A and L_B and their effective temperatures are denoted T_{effA} and T_{effB} . Stellar classifications are given in the columns headed ”class A” and ”class B”.

HIP ID	a_b	e_b	I	d	M_A	M_B	L_A	L_B	T_{effA}	T_{effB}	class A	class B
14669	9.0	0.14	96.8	15.8	0.56	0.39	0.096	0.026	3580	3370	M2	M4
30920	4.3	0.37	51.8	4.1	0.22	0.08	0.007	0.001	3370	3145	M4V	M5.5V
31711	42.7	0.34	93.9	21.3	1.03	0.57	1.137	0.109	5860	4060	G2V	K7Ve
44248	10.4	0.15	131.4	16.1	1.44	0.89	4.285	0.638	6740	5250	F3V	K0V
45343	97.2	0.28	21.0	5.8	0.52	0.51	0.073	0.067	3850	3850	M0V	M0V
51986	9.9	0.75	129.1	26.8	1.88	1.29	12.535	2.790	6710	6740	F4IV	F3
58001	11.7	0.30	51.0	25.5	2.94	0.79	65.255	0.397	9520	4780	A0Ve	K2V
64241	11.8	0.50	90.1	17.8	1.30	1.12	2.887	1.553	6440	6360	F5V	F6V
64797	89.2	0.12	93.4	11.1	0.73	0.52	0.277	0.072	5015	3715	K1V	M1V
66492	46.9	0.61	36.3	22.0	0.59	0.48	0.121	0.054	3782	3647	M0.5	M1.5
67422	32.7	0.45	47.4	13.4	0.72	0.65	0.273	0.174	4560	4205	K4V	K6V
84425	7.7	0.49	115.2	30.6	1.23	0.86	2.267	0.556	6280	5860	F7V	G2V
84720	91.6	0.78	35.6	8.8	0.79	0.50	0.393	0.062	5570	3850	G8V	M0V
87895	2.4	0.41	68.0	28.2	1.19	0.90	2.031	0.648	5860	4780	G2V	K2V
93825	32.7	0.32	149.6	17.3	1.27	1.25	2.570	2.432	6200	6200	F8V	F8V
101916	15.7	0.80	107.0	30.1	1.61	0.37	6.794	0.023	5745	4420	G1IV	K2IV
106972	5.3	0.29	69.4	24.5	0.57	0.43	0.105	0.033	3370	3370	M2	M4
114922	6.7	0.44	117.1	30.8	0.49	0.52	0.059	0.073	3715	3580	M1	M2
116132	42.5	0.20	123.5	6.2	0.38	0.20	0.025	0.006	3370	3305	M4	M5
	[AU]		[deg]	[pc]	[M_\odot]	[M_\odot]	[L_\odot]	[L_\odot]	[K]	[K]		

we are investigating, gravitational interactions will alter the planetary orbit.

Perturbation theory of hierarchical triples predicts, that the orbit of the inner pair - in our case host-star and planet - will experience significant alterations in its eccentricity, whereas its semimajor axis remains almost constant (Marchal 1990; Georgakarakos 2002, 2003). For nearly equi-planar systems, the influence of planetary inclination and ascending node to the overall dynamics can be considered small, they will be neglected in what follows. Even-though there may be short periodic variations, some important changes in a planet’s orbit happen also on secular timescales. Secular periods are usually much larger than the planet’s orbital period. However, they are a lot smaller than stellar evolutionary timescales for detached binary systems with semimajor axes $a_b < 100$ AU. It is thus necessary to include the effects of changing planetary orbits in our estimates regarding HZs within binary star environments. In their work, EG12 confirmed that variations in the planet’s orbit are even more important for changes in its insolation than the additional radiation from the second star! The only exceptions to this rule are systems where the second star is much more luminous than the planet’s host-star ($L_B/L_A > 4$, where binary component A is the planet’s host-star in this case). Therefore, a planet’s eccentricity is a dominating factor in determining habitability. Yet, how eccentric can a planetary orbit become, in order to still allow for habitability?

Williams & Pollard (2002) concluded that an Earth-like atmosphere together with surface oceans can buffer the harsh changes between high insolation at periastron and long cold phases near apoastron up to eccentricities of $e_p \approx 0.7$, as long as the average insolation is comparable with the current insolation of the Earth. Although planetary eccentricities of such magnitude are usually not reached in close S-Type setups (EG12), the region where

the planet remains within classical insolation boundaries is still strongly impacted. In order to distinguish orbital zones that are only habitable ”on average” and zones where the planet will never exceed classical insolation limits, EG12 introduced three types of HZs for binary star systems:

Permanently Habitable Zone (PHZ): The PHZ is the region where a planet stays within habitable insolation limits for all times, despite the changes its orbit experiences due to gravitational interactions with the secondary. For this study, we have chosen the classical run-away/maximum greenhouse insolation limits as defined by Kasting et al. (1993) and Underwood et al. (2003) (**KHZ**)

Extended Habitable Zone (EHZ): The binary-planet configuration is still considered to be habitable when most of its orbit remains within the HZ boundaries. This is true if the average received insolation plus one standard deviation does not put the planet beyond KHZ insolation limits.

Averaged Habitable Zone (AHZ): Even an elevated planetary eccentricity ($e < 0.7$) may not be prohibitive for habitability since the atmosphere acts as a buffer (Williams & Pollard 2002), if the time averaged insolation stays within habitable limits. The AHZ represents such regions.

For details on the definition and calculation of PHZ, EHZ & AHZ we refer the reader to EG12. We use the interpolation formulae given in Underwood et al. (2003) to calculate effective insolation values for the selected stellar types. After a brief discussion concerning aspects of dynamical stability, the application of the proposed classification scheme to the 19 selected binary star systems will be presented in the next section.

4 DYNAMICAL STABILITY OF CIRCUMSTELLAR PLANETS IN BINARY STARS

As was briefly mentioned during the introduction, there are many open questions regarding the formation of planets in double star environments (Thebault 2011). However, once formed a planet can survive in the dynamically stable region around one of the binary components - a fact proven by observed planets in S-Type binary configurations (Dumusque et al. 2012; Roell et al. 2012; Giuppone et al. 2012). If the necessary dynamical prerequisites are fulfilled, even both stars can harbor planets. Generalized dynamical investigations such as Holman & Wiegert (1999), Pilat-Lohinger & Dvorak (2002), semi-analytical (Pichardo et al. 2005) or analytical approaches (Szebehely & McKenzie 1977; Eggleton 1983) can be used to determine regions where a test-planet can remain on a stable orbit on secular dynamical timescales. As the setup used in this work consists of a planar binary - Earth configuration, the restricted three body approach used in the articles mentioned above can be considered a reasonable approximation. We will apply the numerical fit by Holman & Wiegert (1999) and results by Pilat-Lohinger & Dvorak (2002) to find critical semimajor axis for circumstellar motion.

5 RESULTS

The different HZs discussed in section 3 are presented for a fictitious Earth-like planet in each of the selected double star systems (Fig. 1). The region of instability (striped) is also marked. The left graph of Fig. 1 represents HZs around the primary (S-Type A), and the right graph shows HZs around the secondary (S-Type B) (Whitmire et al. 1998). Black (red online) denotes regions which are non-habitable due to excessive or insufficient insolation, dark gray (yellow online), medium gray (green online) and light gray (blue online) represent the AHZ, EHZ and PHZ respectively. Dashed and full 'I' symbols give the inner and outer borders of the classical HZ as defined by Kasting et al. (1993) and Underwood et al. (2003) (KHZ). Eggl et al. (2012b) found a good correspondence between the KHZ and the AHZ, which is also mirrored in the results at hand. Exceptions are the systems HIP 58001 & 101916 where the more luminous companion shifts the HZs of the less luminous one considerably. Out of the 19 selected systems, 17 permit Earth-like planets in HZs on dynamically stable orbits around at least one stellar component. In total, the 17 habitable systems feature 16 M, 7 K, 3 G and 5 F class stars. Even if the all F and M class stars were to be excluded from the list of hosts for HZ - either because of their comparatively short lifespans (Kasting et al. 1993) or tidal and radiative effects (see section 7) - more than 26% of the stars in this sample would be capable of sustaining habitable planets on secular dynamical timescales. If the stars' mass loss via stellar winds is negligible, and no cataclysmic events occur (Veras & Tout 2012), habitability might be given even for stellar evolutionary timescales.

A detailed listing of HZ-borders as well as expected radial velocity (RV) and astrometric (AM) signal strengths

produced by a terrestrial planet in the selected systems is presented in Tables 2 - 4. Maximum and root mean square (rms)¹ signal strengths have been calculated following Eggl et al. (2012a). The corresponding equations are repeated in appendix A for the reader's convenience. Comparing AM and RV signal strengths one can see that - current observational equipment assumed - RV seems to stand a better chance to find Earth-like planets in HZs of nearby double stars. With the discovery of α Cen B b the currently feasible RV resolution is approximately 50 cm/s. For the detection of habitable planets in the α Centauri system, however, semi-amplitudes around 10 cm/s would be required (Eggl et al. 2012a). Possible candidate systems such as HIP 14699, 30920, 106972, 114922 or 116132 would offer better conditions for finding habitable Earth analogues via RV than α Centauri does.

As 9 out of the 17 potentially habitable systems feature M-stars, it is worth mentioning that determining the effective insolation a terrestrial planet receives might not be enough to claim habitability. In fact, Lammer et al. (2011) are convinced that the potentially elevated level of X-ray and extreme UV radiation in M-stars might lead to a different atmospheric evolution of an Earth-like planet in an M-star's HZ, thus preventing the existence of life as we know it. Ultimately direct observation of the interaction between stellar and planetary atmospheres will be necessary to determine to which degree planets can remain habitable in the vicinity of M-type stars. The proposed transit spectroscopy mission ECHO (Tinetti et al. 2012) can be a step in this direction, although currently only super-Earths down to 1.5 r_{\oplus} around K-F stars are planned to be observed. With RV signal amplitudes of $\approx 5 - 12$ cm/s for potentially habitable planets in systems containing Sun-like G stars (HIP 31711 & 84425), our estimates are comparable to those for α Centauri presented in Eggl et al. (2012a) and Guedes et al. (2008). Detecting planets around Sun-like stars would therefore require a considerable amount of dedicated observation time (Dumusque et al. 2012; Guedes et al. 2008).

The AM amplitudes determined for the 19 systems at hand are well below 1 μ as. This will put the systems in consideration even beyond the reach of ESA's GAIA mission (Hestroffer et al. 2010). However, recently Malbet et al. (2011) proposed the Nearby Earth Astrometric Telescope (NEAT) which would be capable of resolving astrometric motion down to 0.05 μ as at a one σ accuracy level. This instrument would be able to identify habitable planets in most of the presented binary star systems. Such a mission would indeed be valuable, since AM does not only favor planet detection in binary configurations with Sun-like components - their HZs are further away from their host stars thus producing larger AM amplitudes - it would more importantly grant observational access to all the planet's orbital parameters. Especially mutual inclinations are of interest in this case, as they could provide answers to many important problems regarding planet-formation as well as migration in binary star systems (Batygin et al. 2011; Thebault 2011; Wu & Murray 2003).

¹ In this case rms values have not only been time averaged, but they were also averaged over the planet's argument of pericenter.

6 POTENTIALLY TRANSITING SYSTEMS

With an inclination of $I \approx 90^\circ$ with respect to the plane of the sky the systems HIP 14669, 31711, 64241 & 64797 could harbor transiting planets that still would be compatible with our assumptions of a planar binary planet configuration. Assuming non grazing transits, i.e. transits where less than the full planetary disc obscures the stellar surface during transit, and neglecting entry as well as limb darkening effects, we can estimate the relative transit depth (TD) that the planet will cause in its host-star's photometric signal:

$$TD \simeq \frac{R_p^2}{R_\star^2} \quad (1)$$

Hereby, R_p and R_\star denote the planetary and stellar radii respectively. Table 5 shows the relative transit depths for Earth-like planets in systems allowing for transits while still being close to planar. Even-though some stellar components are on the verge of being too bright to be observed by *Kepler*, the spacecraft's current performance (combined noise level ≈ 29 ppm, Gilliland et al. (2011)), would allow for an Earth-like planet in circumstellar HZs to be found in all of these systems given sufficient observation time.

7 TIDAL LOCKING

An orbital state, where the planet rotates around its own axis with the same speed as it orbits its host-star - much like the Moon around the Earth - is called 1:1 spin-orbit resonance. A star-planet system might evolve into such a state due to tidal interactions (see e.g. Murray & Dermott (1999)). Therefore, this state is often referred to as tidal lock. Since a tidal locking potentially adds additional instabilities to a planet's climate (Kite et al. 2011), regions where 1:1 spin orbit resonances occur are usually excluded from HZs. Kasting et al. (1993) used an equation dating back to Peale (1977) to calculate the distance up to which a planet would be tidally locked in a time-span equal to age of the Solar System. Inserting such values as chosen in Kasting et al. (1993) the simple estimate reads:

$$r_{TL} \approx 0.46 \left(\frac{AU}{M_\odot^{1/3}} \right) m_\star^{1/3} \quad (2)$$

with r_{TL} denoting the tidal locking radius in AU and m_\star the mass of the host star in M_\odot . Applying this estimate to our selected systems indicates that all HZs in M-M binaries fall at least partly in the Tidal Locking Zone. However, tidal evolution of a planet in a binary system is much more involved than simple two body dynamics can account for, as the angular momentum transfer between the host-star-planet system and the secondary needs to be included in the model. Eggleton (2006) provides analytical estimates for the tidal evolution of stellar hierarchical triple systems showing that in fact many possible resonant states other than 1:1 spin-orbit locking exists for the inner pair although with different degrees of stability. Wu & Murray (2003) and Fabrycky & Tremaine (2007) investigated the possibility for tidal migration of planets due to mutually inclined massive perturbers via Kozai cycles (Kozai 1962). Yet, as point out by Correia et al. (2011), only quadrupolar secular expansions had been used to evaluate the planet's eccentricity,

which give inaccurate results for low inclination configurations such as discussed in the study at hand (Lee & Peale 2003). Similar to Eggleton (2006), Correia et al. (2011) show that tidal interactions in inclined hierarchical triple systems can produce many different outcomes, especially when the component's changes in obliquity are taken into account. Their system's final states included transformations of retrograde to prograde motion and vice versa, a decay of mutual inclination and rapid circularization of the inner planetary orbit as well as tidally induced migration. As more detailed tidal interaction models require knowledge of the stellar radii (Correia et al. 2011; Eggleton 2006), the model dependence of radii for M-dwarfs adds another source of uncertainty, see e.g. Muirhead et al. (2012).

The lack of accurate analytical tools to study the influence of tidal interactions in planar S-Type configurations as well as the wealth of possible final states depending on the system's initial conditions put a detailed analysis of the planet-binary system's tidal evolution beyond the scope of this work.

8 SUMMARY

Applying the analytic methods presented in (Eggl et al. 2012a,b) we have shown that 17 out of 19 binary star systems with well determined stellar and orbital parameters close to the Solar System allow for dynamically stable Earth-like planets in circumstellar habitable zones (HZs). Four of these habitable systems feature F, three feature G, six feature K, and nine feature M class stars. Not surprisingly, M-M binary constellations offer the best chances for detecting planets in HZs via radial velocity observations. However, determining habitability in M star doublets may require additional considerations such as tolerable stellar X-ray and EUV fluxes (Lammer et al. 2011) or the system's potential for tidally locking the planet to its host star (see section 7). Habitable planets in systems featuring G-type stars have RV amplitudes comparable to the ones found for α Centauri AB (Eggl et al. 2012a; Guedes et al. 2008). The systems HIP 14699, 30920, 106972, 114922 or 116132 would be promising candidates to search for terrestrial planets in their HZs, as they offer best case RV semi-amplitudes comparable to α Centauri B b (Dumusque et al. 2012). Four of the 17 systems would allow for transiting planets in HZs, which could be detected using current technology. Their mid transit depths were estimated to lie between 44 and 369 ppm with planetary periods ranging from 235 to 476 days. Astrometric signal amplitudes for Earth-like planets in all the investigated systems' HZs are, in contrast, well below $1 \mu\text{as}$. Therefore, dedicated missions such as NEAT (Malbet et al. 2011) will be required in order to detect habitable worlds in binary stars via astrometry. A sample of 19 systems does not offer the possibility to construct a reasonable statistical analysis on the number of potentially habitable binary star systems in the Solar neighborhood. More precise data on spectral types and orbital elements of nearby double stars are required in this respect. Nevertheless, our findings indicate that including binary star systems with $1 < a_b < 100$ in observational campaigns has the potential to enhance our chances of finding habitable worlds.

Table 2. Critical semimajor axis (a_{crit} [AU], col. 3) for orbital stability and borders for the HZs ([AU], cols. 5-9) as measured for the respective host stars A&B are given for 19 binary star systems in the Solar neighborhood. Additionally, rms radial velocity (RV [cm/s]) and astrometric (AM [μ as]) signatures of terrestrial planets have been evaluated at the HZ borders. The conditions required for a planet to be within the Averaged (AHZ), Extended (EHZ) and Permanent (PHZ) Habitable Zone are discussed in section 3. Dashed fields (-) represent cases where a given HZ border lies beyond the critical semimajor axis a_{crit} . Planets there would be on dynamically unstable orbits.

HIP ID	comp.	a_{crit}	inner AHZ	inner EHZ	inner PHZ	outer PHZ	outer EHZ	outer AHZ	
14669	A (M2)	2.287	0.306	0.308	0.310	0.590	0.596	0.604	HZ
			22.02	21.95	21.88	16.04	15.96	15.86	max RV
			15.39	15.34	15.29	11.09	11.03	10.96	rms RV
			0.107	0.108	0.109	0.209	0.211	0.214	max AM
			0.076	0.076	0.077	0.146	0.147	0.149	rms AM
	B (M4)	1.806	0.162	0.162	0.162	0.316	0.318	0.320	HZ
			36.00	36.00	36.00	25.94	25.86	25.78	max RV
			25.30	25.30	25.30	18.12	18.06	18.00	rms RV
			0.081	0.081	0.081	0.159	0.160	0.161	max AM
			0.057	0.057	0.057	0.112	0.112	0.113	rms AM
30920	A (M4V)	0.865	0.086	0.086	0.088	0.162	0.166	0.168	HZ
			52.37	52.37	51.80	38.90	38.47	38.26	max RV
			36.24	36.24	35.83	26.43	26.11	25.95	rms RV
			0.291	0.291	0.298	0.557	0.571	0.578	max AM
			0.237	0.237	0.242	0.445	0.456	0.462	rms AM
	B (M5.5V)	0.470	0.027	0.027	0.027	0.051	0.051	0.051	HZ
			157.79	157.79	157.79	115.07	115.07	115.07	max RV
			110.84	110.84	110.84	80.36	80.36	80.36	rms RV
			0.255	0.255	0.255	0.487	0.487	0.487	max AM
			0.210	0.210	0.210	0.400	0.400	0.400	rms AM
31711	A (G2V)	8.351	0.886	0.894	0.902	1.694	1.724	1.756	HZ
			9.63	9.59	9.55	7.09	7.03	6.97	max RV
			6.68	6.65	6.62	4.83	4.79	4.74	rms RV
			0.125	0.126	0.127	0.243	0.247	0.252	max AM
			0.087	0.088	0.088	0.166	0.169	0.172	rms AM
	B (K7Ve)	5.848	0.316	0.318	0.320	0.614	0.618	0.622	HZ
			21.36	21.29	21.23	15.42	15.37	15.32	max RV
			15.00	14.95	14.90	10.76	10.72	10.69	rms RV
			0.079	0.080	0.080	0.155	0.156	0.157	max AM
			0.056	0.056	0.056	0.108	0.109	0.109	rms AM
44248	A (F3V)	2.686	1.581	1.619	1.697	2.686	2.686	2.686	HZ
			4.80	4.75	4.66	-	-	-	max RV
			3.19	3.15	3.08	-	-	-	rms RV
			0.221	0.226	0.238	-	-	-	max AM
			0.176	0.181	0.189	-	-	-	rms AM
	B (K0V)	1.967	0.710	0.718	0.734	1.340	1.418	1.456	HZ
			8.76	8.71	8.62	6.59	6.44	6.38	max RV
			6.03	6.00	5.93	4.39	4.27	4.21	rms RV
			0.154	0.156	0.160	0.300	0.320	0.329	max AM
			0.127	0.129	0.132	0.241	0.255	0.262	rms AM
45343	A (M0V)	17.932	0.263	0.263	0.263	0.515	0.515	0.517	HZ
			8.79	8.79	8.79	6.30	6.30	6.28	max RV
			6.20	6.20	6.20	4.43	4.43	4.43	rms RV
			0.265	0.265	0.265	0.520	0.520	0.522	max AM
			0.256	0.256	0.256	0.501	0.501	0.503	rms AM
	B (M0V)	17.698	0.252	0.252	0.254	0.494	0.496	0.496	HZ
			9.08	9.08	9.04	6.50	6.48	6.48	max RV
			6.41	6.41	6.38	4.58	4.57	4.57	rms RV
			0.259	0.259	0.261	0.509	0.511	0.511	max AM
			0.250	0.250	0.252	0.491	0.493	0.493	rms AM
51986	A (F4IV)	0.545	-	-	-	-	-	-	HZ
	B (F3)	0.448	-	-	-	-	-	-	HZ
58001	A (A0Ve)	2.828	-	-	-	-	-	-	HZ
	B (K2V)	1.331	0.639	0.653	0.775	1.263	1.331	1.331	HZ
			10.31	10.21	9.46	7.85	-	-	max RV
			6.98	6.91	6.34	4.97	-	-	rms RV
			0.100	0.102	0.123	0.210	-	-	max AM
			0.080	0.082	0.097	0.159	-	-	rms AM

Table 3. Continuation of Table 2. Radial velocity (RV) amplitudes are given in [cm/s], astrometric (AM) amplitudes in [μ as]. The critical planetary semimajor axis a_{crit} as well as the HZ borders are given in [AU].

HIP ID	comp.	a_{crit}	inner AHZ	inner EHZ	inner PHZ	outer PHZ	outer EHZ	outer AHZ	
64241	A (F5V)	1.465	1.354	1.465	1.465	1.465	1.465	1.465	HZ
			8.19	-	-	-	-	-	max RV
			4.82	-	-	-	-	-	rms RV
			0.209	-	-	-	-	-	max AM
			0.126	-	-	-	-	-	rms AM
	B (F6V)	1.339	1.002	1.056	1.226	1.339	1.339	1.339	HZ
			9.76	9.58	9.15	-	-	-	max RV
			6.05	5.90	5.47	-	-	-	rms RV
			0.173	0.184	0.219	-	-	-	max AM
			0.109	0.115	0.133	-	-	-	rms AM
64797	A (K1V)	23.212	0.472	0.472	0.474	0.924	0.926	0.926	HZ
			15.48	15.48	15.45	11.08	11.07	11.07	max RV
			10.93	10.93	10.91	7.81	7.80	7.80	rms RV
			0.179	0.179	0.180	0.351	0.352	0.352	max AM
			0.126	0.126	0.127	0.248	0.248	0.248	rms AM
	B (M1V)	18.564	0.263	0.263	0.263	0.517	0.517	0.517	HZ
			24.51	24.51	24.51	17.50	17.50	17.50	max RV
			17.32	17.32	17.32	12.35	12.35	12.35	rms RV
			0.140	0.140	0.140	0.275	0.275	0.275	max AM
			0.099	0.099	0.099	0.194	0.194	0.194	rms AM
66492	A (M0.5)	4.289	0.339	0.341	0.345	0.645	0.655	0.667	HZ
			12.20	12.17	12.10	8.99	8.92	8.85	max RV
			8.48	8.46	8.41	6.15	6.10	6.05	rms RV
			0.081	0.081	0.082	0.156	0.158	0.161	max AM
			0.072	0.072	0.073	0.137	0.139	0.142	rms AM
	B (M1.5)	3.835	0.227	0.229	0.231	0.439	0.443	0.449	HZ
			16.40	16.33	16.26	11.92	11.87	11.80	max RV
			11.46	11.41	11.36	8.24	8.21	8.15	rms RV
			0.066	0.066	0.067	0.129	0.130	0.132	max AM
			0.059	0.060	0.060	0.114	0.115	0.117	rms AM
67422	A (K4V)	4.503	0.486	0.490	0.496	0.916	0.934	0.952	HZ
			11.47	11.43	11.36	8.51	8.43	8.36	max RV
			7.95	7.92	7.87	5.79	5.74	5.68	rms RV
			0.155	0.157	0.159	0.298	0.304	0.310	max AM
			0.130	0.131	0.133	0.245	0.250	0.255	rms AM
	B (K6V)	4.212	0.398	0.400	0.404	0.754	0.766	0.780	HZ
			13.37	13.34	13.27	9.85	9.78	9.70	max RV
			9.30	9.27	9.23	6.75	6.70	6.64	rms RV
			0.142	0.143	0.144	0.273	0.277	0.282	max AM
			0.119	0.120	0.121	0.226	0.229	0.234	rms AM
84425	A (F7V)	1.024	-	-	-	-	-	-	HZ
	B (G2V)	0.835	0.635	0.667	0.797	0.835	0.835	0.835	HZ
			12.54	12.32	11.67	-	-	-	max RV
			7.82	7.63	6.98	-	-	-	rms RV
			0.082	0.087	0.107	-	-	-	max AM
			0.056	0.059	0.071	-	-	-	rms AM
84720	A (G8V)	4.275	0.535	0.543	0.551	1.003	1.029	1.057	HZ
			8.34	8.29	8.23	6.25	6.17	6.10	max RV
			5.73	5.69	5.65	4.19	4.13	4.08	rms RV
			0.240	0.244	0.248	0.461	0.474	0.487	max AM
			0.213	0.216	0.219	0.399	0.410	0.421	rms AM
	B (M0V)	3.364	0.242	0.242	0.244	0.462	0.468	0.474	HZ
			15.40	15.40	15.33	11.27	11.20	11.14	max RV
			10.75	10.75	10.70	7.78	7.73	7.68	rms RV
			0.170	0.170	0.172	0.329	0.333	0.337	max AM
			0.153	0.153	0.154	0.292	0.296	0.300	rms AM
87895	A (G2V)	0.371	-	-	-	-	-	-	HZ
	B (K2V)	0.312	-	-	-	-	-	-	HZ

Table 4. Continuation of Table 2. Radial velocity (RV) amplitudes are given in [cm/s], astrometric (AM) amplitudes in [μ as]. The critical planetary semimajor axis a_{crit} as well as the HZ borders are given in [AU].

HIP ID	comp.	a_{crit}	inner AHZ	inner EHZ	inner PHZ	outer PHZ	outer EHZ	outer AHZ	
93825	A (F8V)	5.623	1.289	1.311	1.337	2.421	2.505	2.581	HZ
			3.71	3.68	3.65	2.79	2.74	2.71	max RV
			2.54	2.51	2.49	1.85	1.82	1.79	rms RV
			0.185	0.189	0.193	0.358	0.371	0.383	max AM
			0.168	0.170	0.174	0.315	0.326	0.336	rms AM
	B (F8V)	5.575	1.254	1.274	1.300	2.358	2.438	2.512	HZ
			3.79	3.76	3.72	2.84	2.80	2.76	max RV
			2.59	2.57	2.54	1.89	1.86	1.83	rms RV
			0.183	0.186	0.190	0.353	0.365	0.377	max AM
			0.165	0.168	0.171	0.311	0.321	0.331	rms AM
101916	A (G1IV)	0.754	-	-	-	-	-	-	HZ
	B (K2IV)	0.381	0.155	0.159	0.233	0.261	0.381	0.381	HZ
			38.16	37.73	31.89	30.40	-	-	max RV
			25.63	25.31	20.91	19.75	-	-	rms RV
			0.045	0.046	0.069	0.078	-	-	max AM
0.031	0.032	0.047	0.053	-	-	rms AM			
106972	A (M2)	1.034	0.322	0.330	0.338	0.588	0.616	0.640	HZ
			20.73	20.50	20.28	15.94	15.65	15.41	max RV
			13.99	13.82	13.65	10.35	10.12	9.93	rms RV
			0.074	0.076	0.077	0.139	0.147	0.153	max AM
			0.053	0.054	0.055	0.096	0.101	0.105	rms AM
	B (M4)	0.865	0.179	0.183	0.185	0.339	0.351	0.359	HZ
			31.41	31.08	30.92	23.35	22.99	22.76	max RV
			21.63	21.40	21.28	15.73	15.46	15.28	rms RV
			0.053	0.055	0.055	0.103	0.107	0.110	max AM
			0.039	0.040	0.040	0.074	0.077	0.078	rms AM
114922	A (M1)	0.897	0.239	0.245	0.251	0.435	0.455	0.473	HZ
			24.59	24.31	24.05	18.89	18.53	18.24	max RV
			16.60	16.40	16.20	12.30	12.03	11.80	rms RV
			0.050	0.051	0.053	0.094	0.099	0.103	max AM
			0.037	0.038	0.039	0.068	0.071	0.074	rms AM
	B (M2)	0.924	0.266	0.272	0.282	0.480	0.504	0.528	HZ
			22.83	22.60	22.23	17.67	17.32	17.00	max RV
			15.33	15.16	14.89	11.41	11.14	10.88	rms RV
			0.053	0.055	0.057	0.100	0.105	0.111	max AM
			0.039	0.040	0.042	0.071	0.075	0.078	rms AM
116132	A (M4)	10.619	0.158	0.158	0.158	0.310	0.310	0.312	HZ
			30.77	30.77	30.77	22.02	22.02	21.95	max RV
			21.72	21.72	21.72	15.51	15.51	15.46	rms RV
			0.204	0.204	0.204	0.401	0.401	0.404	max AM
			0.165	0.165	0.165	0.323	0.323	0.325	rms AM
	B (M5)	7.091	0.076	0.076	0.076	0.152	0.152	0.152	HZ
			60.97	60.97	60.97	43.14	43.14	43.14	max RV
			43.07	43.07	43.07	30.45	30.45	30.45	rms RV
			0.184	0.184	0.184	0.369	0.369	0.369	max AM
			0.149	0.149	0.149	0.298	0.298	0.298	rms AM

Table 5. Transit depths (TD), visual brightness (V , WDS) and planetary period (P_p) ranges are given for potentially transiting planets in the HZs of those selected binary systems with $I \approx 90^\circ$.

HIP ID	comp.	V [mag]	TD [ppm]	P_p [D]
14669	A	10.32	128	270.80 - 380.35
	B	12.5	369	235.67 - 331.14
31711	A	6.32	78	338.38 - 476.35
	B	9.84	187	270.91 - 380.10
64241	A	4.85	44	372.23
	B	5.53	79	346.09 - 382.82
64797	A	6.66	171	294.45 - 412.52
	B	9.5	198	260.18 - 364.81

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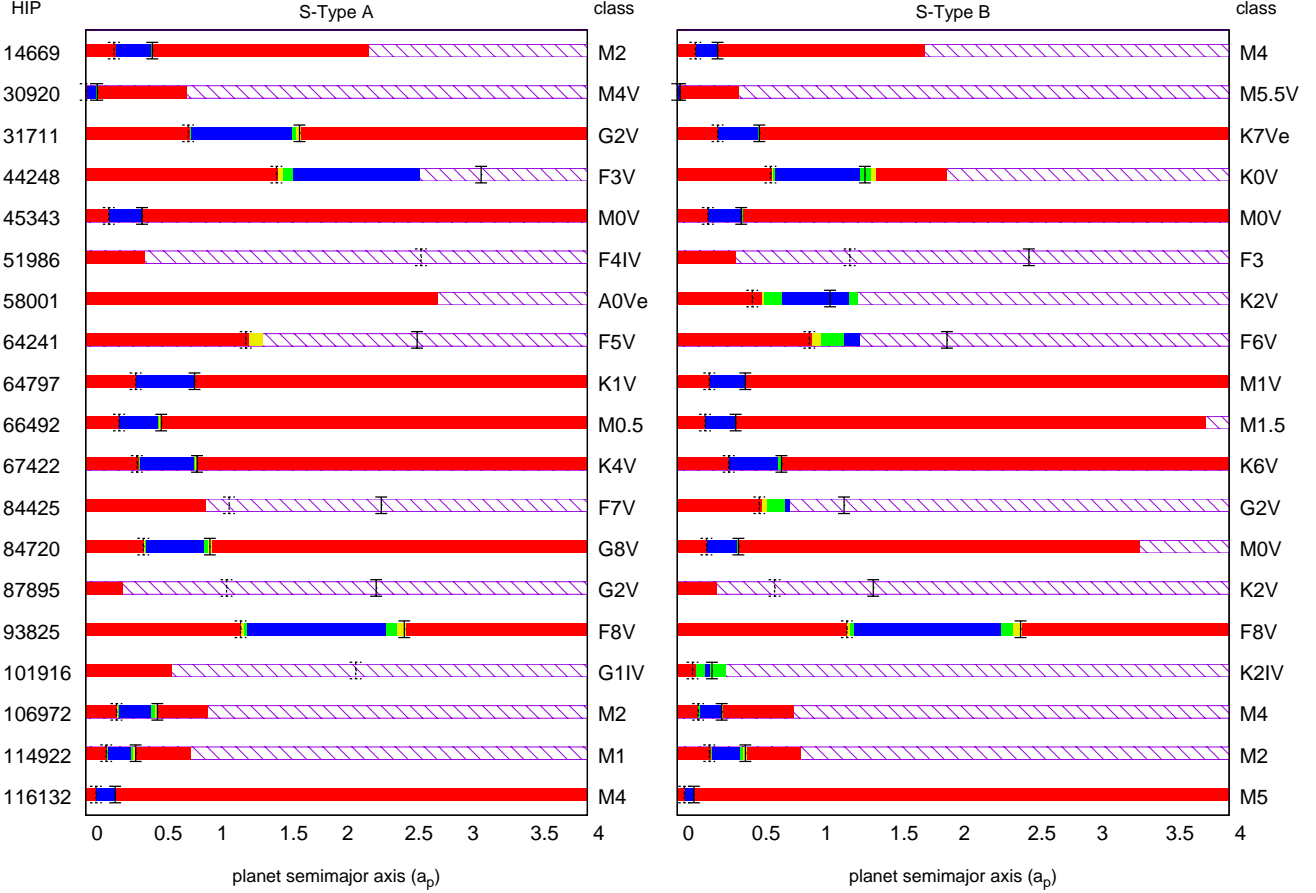


Figure 1. Habitable zones of 19 S-Type binary star systems in the Solar neighborhood are shown. The light gray regions (blue online) denote zones of permanent habitability (PHZ), medium gray (green online) Extended (EHZ) and dark gray (yellow online) Averaged Habitable Zones (AHZ), see section 3. Black (red online) are regions where the planet either receives too much, or too little radiation to keep atmospheric temperatures stable. The striped areas are zones of dynamical instability (Holman & Wiegert 1999). *Left:* HZs around the system’s primary star are shown (S-Type A), *right:* habitability of regions around the secondary are investigated (S-Type B) (Whitmire et al. 1998). The dashed ‘I’ symbols indicate the inner, the full symbols the outer border of the classical HZ as defined by Kasting et al. (1993) & Underwood et al. (2003). In most cases, the AHZ and the classical HZ coincide well as was pointed out in (Eggl et al. 2012b), except for the systems HIP 58001 and 101916 where the considerable luminosity of the brighter companions shift the HZs of the S-Type B configurations to larger planetary semimajor axes. Evidently, 17 out of the 19 investigated systems allow for dynamically stable terrestrial planets within HZs around at least one of its binary’s components.

APPENDIX A: MAXIMUM AND RMS SIGNAL AMPLITUDES

Following Beaugé et al. (2007) & Eggl et al. (2012a) the RV amplitude a planet causes on its host star is given by

$$RV = \frac{\sqrt{G} m_1 \sin I}{\sqrt{m_0 + m_1}} \frac{e \cos \omega + \cos(f + \omega)}{\sqrt{a(1 - e^2)}}, \quad (\text{A1})$$

where G denotes the gravitational constant, m_0 and m_1 are the host-star’s and planet’s masses. The quantities a , e , I and ω denote the planet’s semimajor axis and eccentricity, the system’s inclination to the plane of the sky and the planet’s argument of pericenter respectively. The planet’s true anomaly is represented by f . We can write the maximum possible radial velocity (RV) amplitude caused by a terrestrial planet in a circumstellar orbit around one binary component as follows:

$$\max RV = \frac{\sqrt{G} m_1 \sin I}{\sqrt{m_0 + m_1}} \frac{(1 + e^{\max})}{\sqrt{a(1 - (e^{\max})^2)}}. \quad (\text{A2})$$

The maximum possible eccentricity the planet can acquire due to gravitational interaction with the double star is denoted by e^{\max} (Eggl et al. 2012b). Expressions for the root mean square (rms) values of the RV signal are given as follows (Eggl et al. 2012a):

$$\text{rms } RV = \frac{1}{2\pi} \left[\int_0^{2\pi} RV^2 dM d\omega \right]^{1/2} = \frac{\sqrt{G} m_1 |\sin I|}{\sqrt{2a(m_0 + m_1)}} \quad (\text{A3})$$

In a similar manner we can use the formalism applied in Pourbaix (2002) to determine maximum astrometric (AM) signal strengths:

$$max\ AM = \frac{\mu a(1 + e^{max})}{d} \quad (A4)$$

where d is the observers distance to the observed system, and $\mu = m_1/(m_0 + m_1)$ is the planet-host-star system's mass ratio. The astrometric rms amplitudes are given by:

$$rms\ AM = \frac{\mu a}{2d} \left[3 + \frac{9}{2}\langle e^2 \rangle + \left(1 + \frac{3}{2}\langle e^2 \rangle \right) \cos(2I) \right]^{1/2} \quad (A5)$$

Here, $\langle e^2 \rangle$ is the averaged squared planetary eccentricity. An analytic expression for $\langle e^2 \rangle$ can be found in Georgakarakos (2003, 2005). For a detailed derivation of all rms and maximum signal amplitudes see Eggl et al. (2012a).